Advanced Controls and Gas Path Health Management: Relevance to Propulsion Safety and Affordable Readiness

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DLT Forum

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NASA & DoD Safety-Related Programs

		NASA Aviation Safety Program	DoD Propulsion Safety & Affordable Readiness (P-SAR) Program
Goals	**Safety**	• Improve inherent safety of legacy and new vehicles • Overcome safety technology barriers which would otherwise constrain full realization of the Next Generation Air Transportation System	• Reduce propulsion related Class A mishaps
	Affordability		• Reduce propulsion maintenance costs
	Readiness		• Increase average time on wing
Projects / Elements		• Integrated Vehicle Health Management • Integrated Intelligent Flight Deck • Integrated Resilient Aircraft Controls • Aircraft Aging and Durability	• Hot Section • Cold Section • Mechanical Systems & Drives • Electrical Power Generation • Prognostics & Health Management • Life Management

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Outline

- Aircraft Engine Life Extending Control
- Gas Path Health Management
  - Overview
  - Enhanced Bank of Kalman Filters for Sensor Fault Diagnostics
  - Automated Power Assessment for Turboshaft Engines
- Data Fusion System For Aircraft Engine Foreign Object Damage Detection

Life Extending Controls

- **Goal: Reduce maintenance costs by increasing the average engine on-wing life**

- **Approach**
  - **Life Modeling**
    - Developed a sensor-based Thermomechanical Fatigue (TMF) life model for the first stage cooled stator of the High Pressure Turbine (HPT)
    - Developed a probability of failure model, based on a Weibull distribution, to calculate a components risk of failure based upon its past operating history
    - Included uncertainty in sensor measurements, actuators, and material qualities
  - **Controls**
    - Developed a new control strategy which optimizes the engine core speed (N2) acceleration schedule to minimize TMF damage while maintaining adequate engine rise time

Retired HPT Blades

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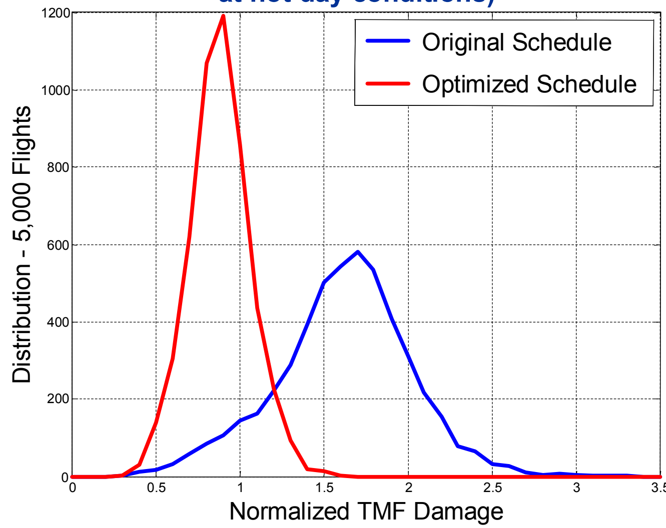
Engine Simulation Demonstration of Life Extending Control Using Stochastic Based Life Models

Comparison of Average TMF Damage Accumulation
(With Varying Ambient Condition and Control Mode)

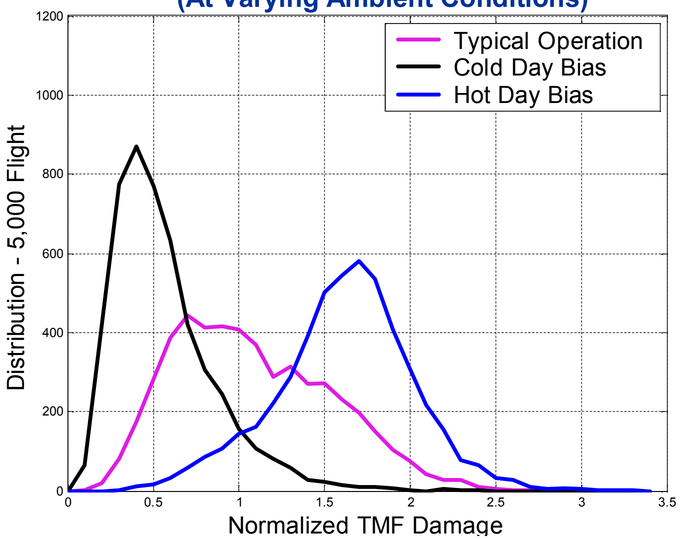
Control / Operating Condition	Original Control Schedule	Optimized Control Schedule
Design Condition	1.0	0.628 (-37.2%)
With Typical Operating Conditions	1.132	0.718 (-36.6%)
Hot Day Bias	1.668	0.931 (-44.2%)
Cold Day Bias	0.609	0.481 (-21.0%)

TMF Damage Accumulation
(Comparison of Original and Optimized Control at hot day conditions)



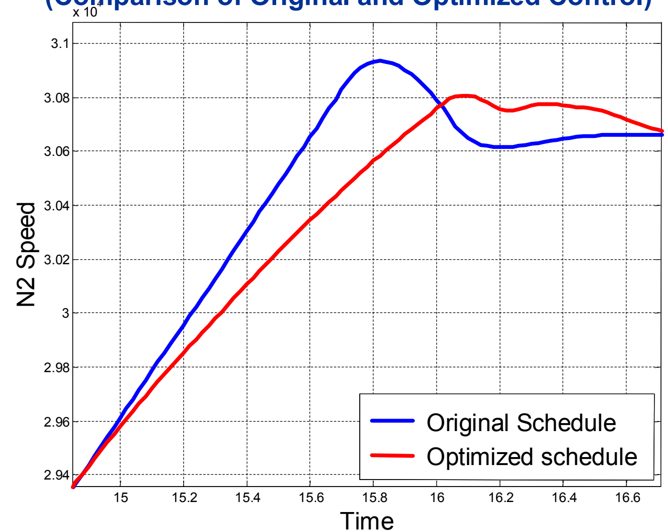
3. Optimized control results in significant component life savings

TMF Damage Accumulation w/ Original Control
(At Varying Ambient Conditions)



1. Component damage accumulation is a function of ambient operating condition

Engine Core Speed Acceleration Response
(Comparison of Original and Optimized Control)



2. Engine control logic can be optimized to minimize damage while maintaining desired engine performance

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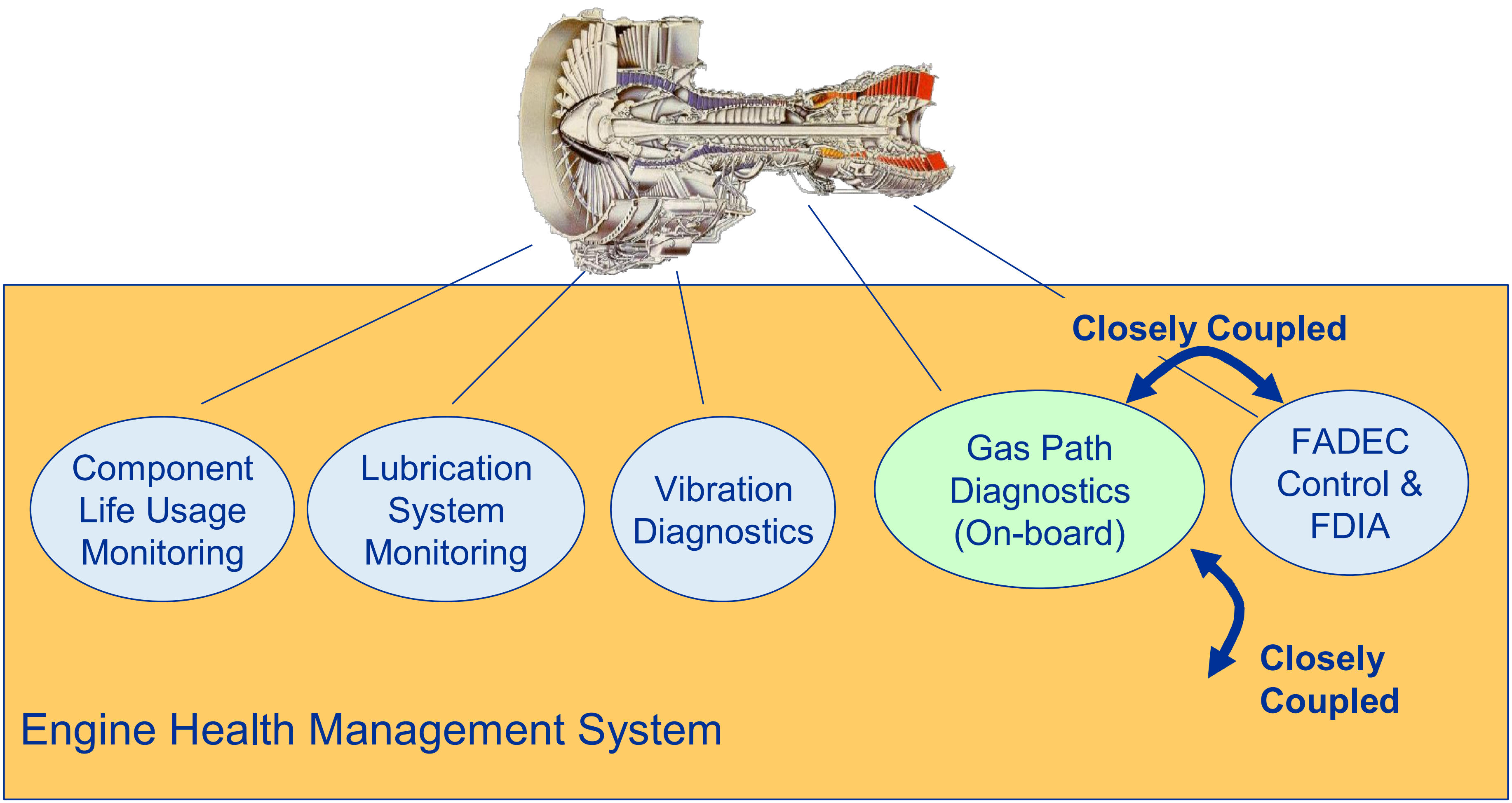
Aircraft Engine Gas Path (Flow Path) Health Management

Gas Path Health Management is a Key Element of an Overall Aircraft Engine Health Management System



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Gas Path Performance Diagnostics Engine Fault Isolation Approach *

A general influence coefficient matrix may be derived for any particular gas turbine cycle, defining the set of differential equations which interrelate the various dependent and independent engine performance parameters.

Physical Problems

- Erosion
- Corrosion
- Fouling
- FOD
- Worn seals or excessive clearance
- Burned, bowed or missing blades
- Plugged nozzles
- Sensor/Actuator Bias

Result in →

← Permitting correction of

Degraded Module Performance

- Flow capacities
- Efficiencies
- Effective nozzle areas
- Expansion coefficients

Producing →

← Allowing isolation of

Changes in Measurable Parameters

- Spool speeds
- Fuel flow
- Temperatures
- Pressures
- Power output

* From "Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines" by Louis A. Urban, 1974

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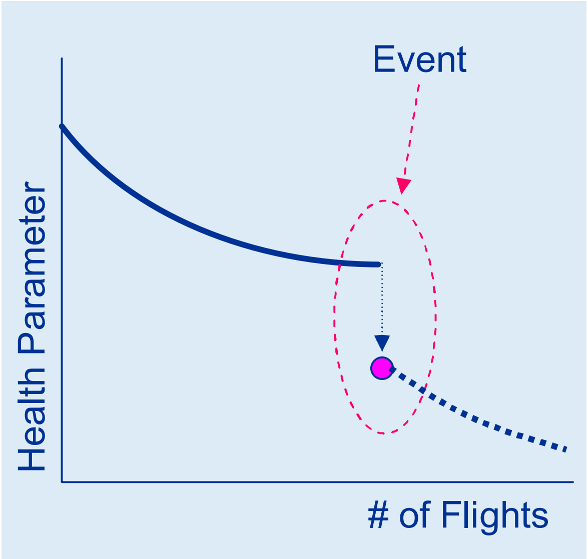
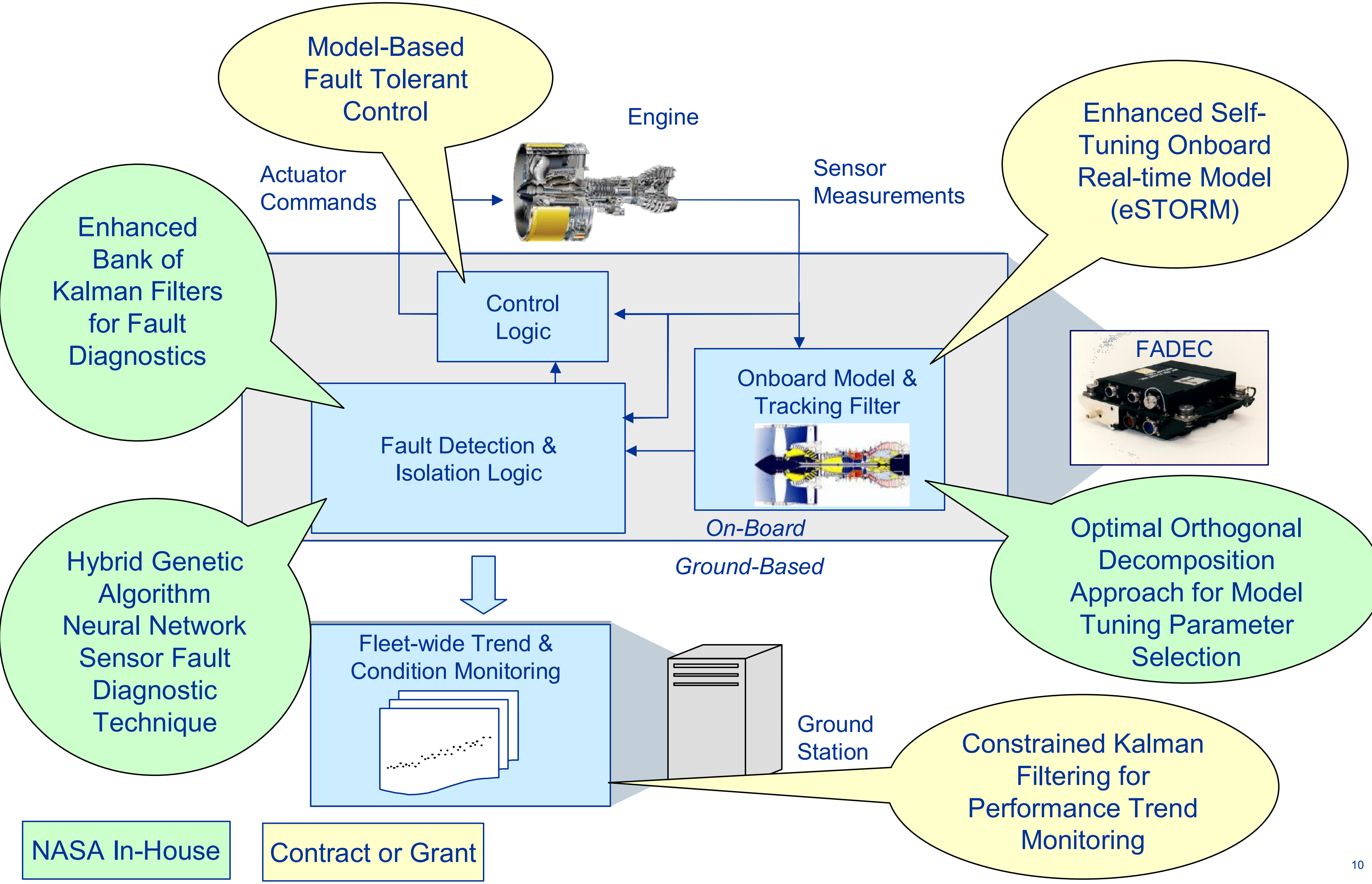
Gas Path Health Management Process

1. Sensing & Data Acquisition
2. Condition/Trend Monitoring
3. Detection
4. Isolation
5. Recommendation

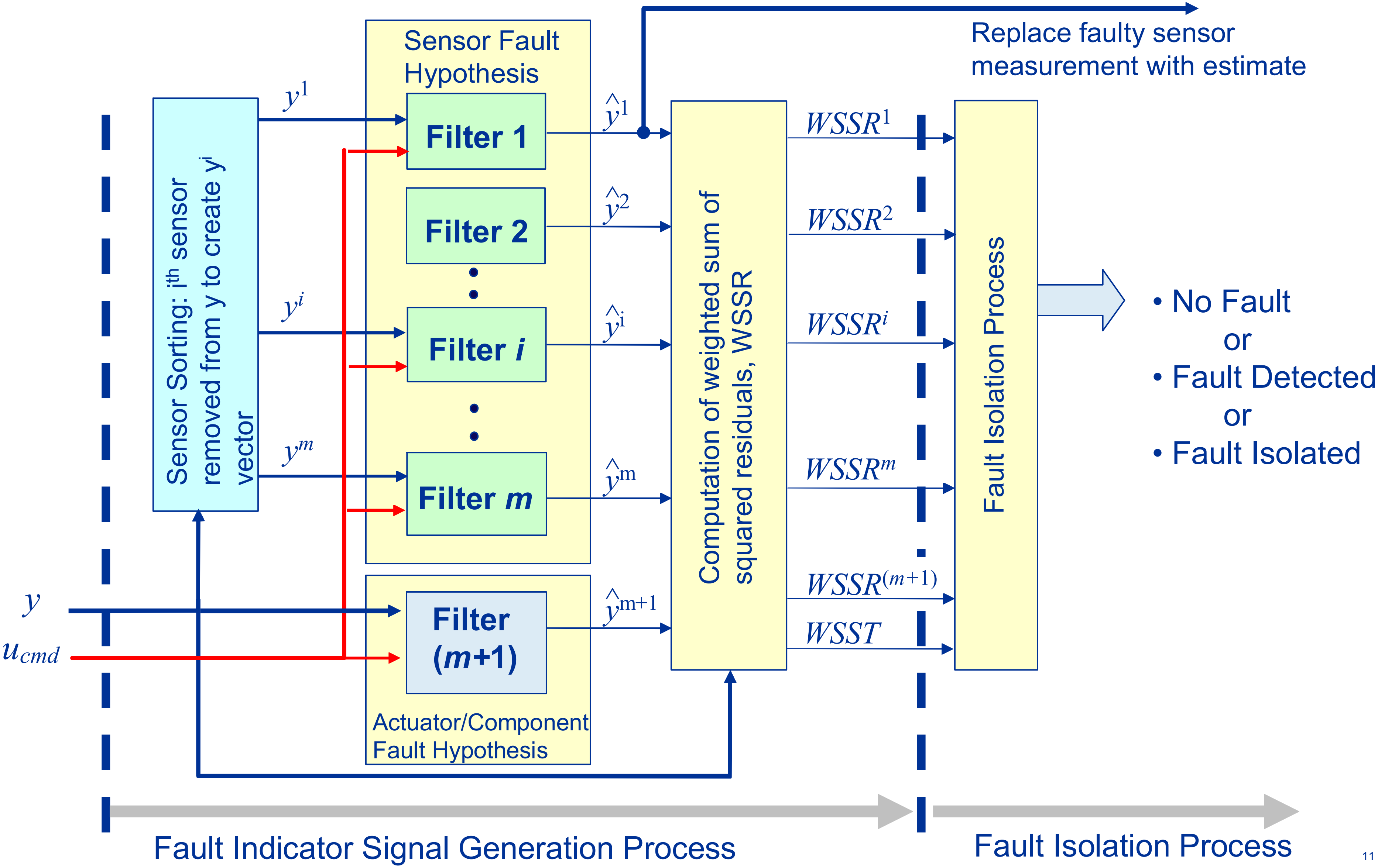


Engine Performance Deterioration and Abrupt Event Illustration

Gas-Path Health Management Architecture & Recent NASA GRC Contributions

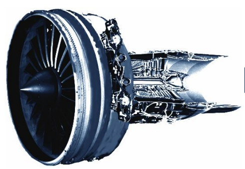


Enhanced Bank of Kalman Filters for Sensor Fault Diagnostics & Accommodation



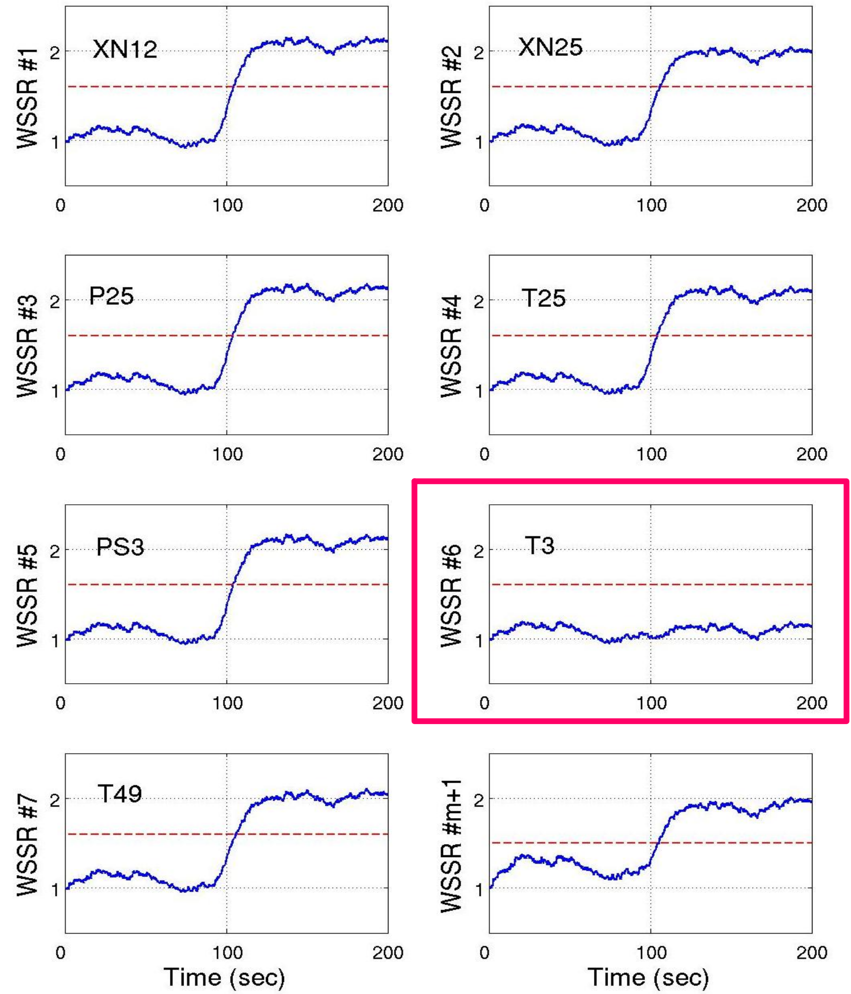
Bank of Kalman Filters Example: Detection & Isolation of a T3 Sensor Bias

Fault



Bank of Kalman Filters

Generate Fault Indicator Signals



WSSR Signals
(T3 Bias Injected @ time = 90 seconds)

Isolation Logic

Assessment: T3 Sensor Faulty

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Automated Power Assessment for Helicopter Turboshaft Engines

- Army Research Laboratory Vehicle Technology Directorate task with Aviation & Missile Research Development and Engineering Center (AMRDEC) Aviation Engineering Directorate (AED)

- Objective: Develop a technique for the automated continuous assessment of available power for helicopter turbo-shaft engines

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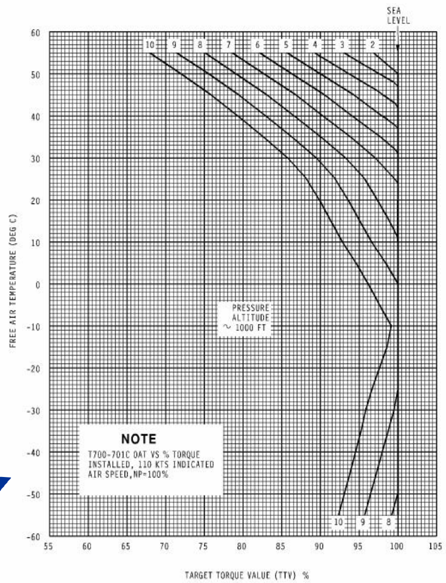
Automated Power Assessment for Helicopter Turboshaft Engines (Background)



ETF Table Lookup

Engine Maximum Power Check (MPC)

- Establishes Engine Torque Factor (ETF), an indication of available engine power
- Requires engine performance data to be collected at altitude while maintaining constant airspeed and operating the engine at a control limit
- ETF determined as a function of recorded parameters and target torque values
- Required when an engine is first installed, or when an engine fails the Health Indicator Test (HIT) Check

Operation in theater

- Desert (sandy) environments significantly accelerates engine deterioration – necessitates more frequent MPCs
- Performing MPCs in theater presents risk of vehicle incurring hostile fire

T700 Stage 1 Blisk Erosion
Source: Westar Aerospace & Defense Group, Inc. Army RIMFIRE Program

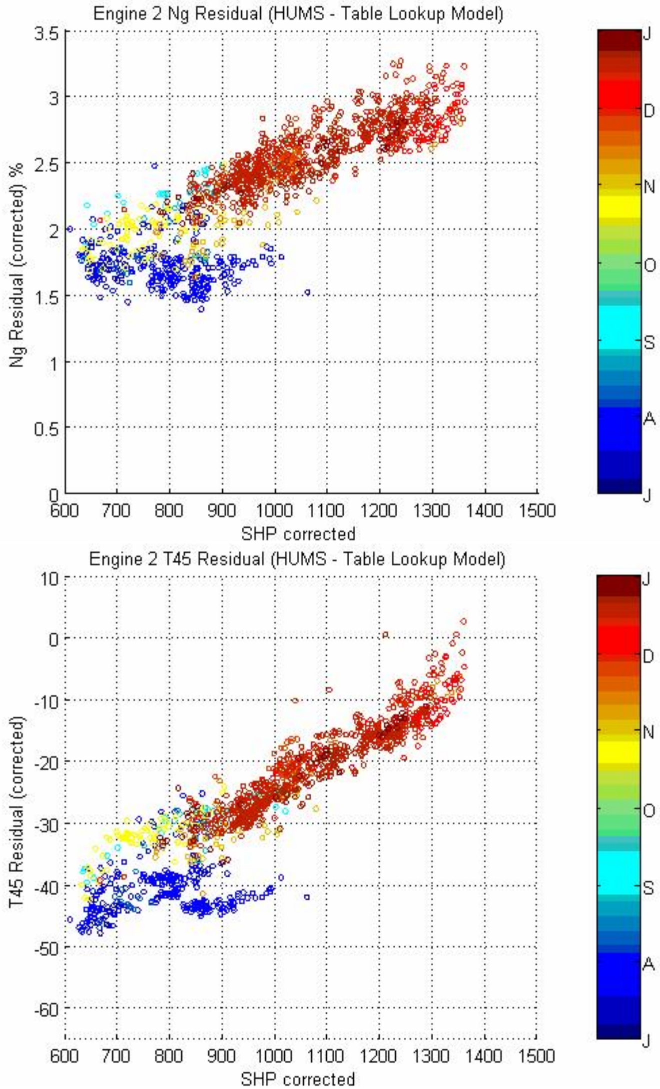
Automated Power Assessment for Helicopter Turboshaft Engines

Progress to date:

- Real-time table lookup model developed to process Health and Usage Monitoring System (HUMS) data
  - Inputs: ambient temperature, ambient pressure, airspeed, and shaft horsepower
  - Outputs: nominal gas generator speed (Ng) and turbine gas temperature (T45)
- Influence coefficient matrices generated to estimate engine performance deterioration from measurement residuals

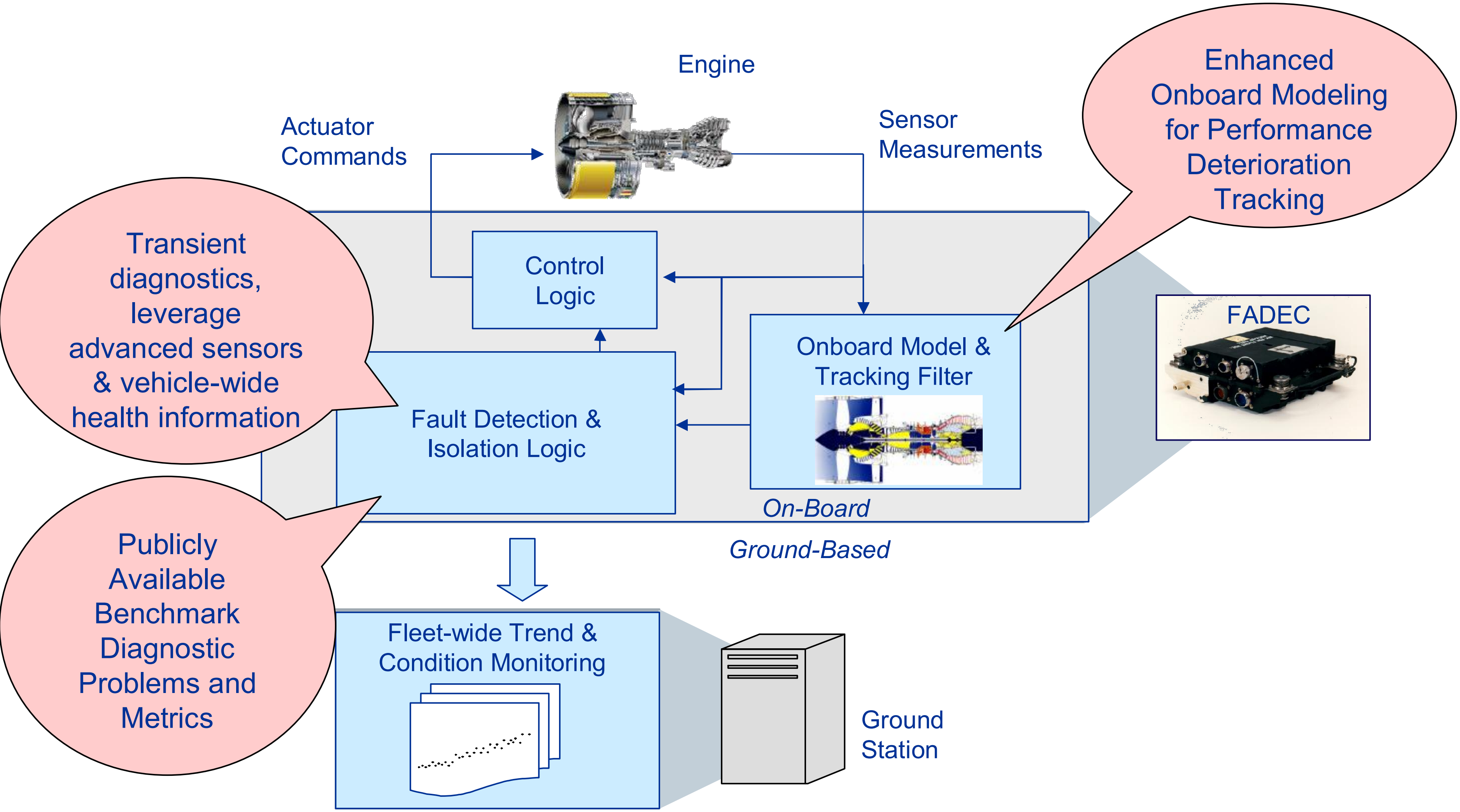
Remaining Tasks:

- Non-uniform update of performance estimates (collected at varying operating conditions over time)
- Extrapolation of performance estimates to high power conditions
- Automation of the Engine Torque Factor (ETF) calculation



Evolution of Ng & T45 residuals for a T700-701C engine over a six month period

Gas-Path Health Management Architecture & NASA GRC IVHM Project Plans (Proposed)



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Data Fusion System For Foreign Object Damage Detection

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Data/Sensor Fusion

- Use multiple disparate sensor suites to observe an event though different eyes.
- Various “domain experts” form an opinion about the event based on the evidence and their knowledge.
- The expert opinions are brought together to support or refute each others’ inferences.
- When experts agree, their final fused opinion carries more weight than individual opinions

Cues and Symptoms of Foreign Object Damage (FOD)

How does the flight crew recognize a FOD event?

- Engine surge, potentially resulting in the loss of power
- Thud or bang
- Fire warning
- Flame coming out of the engine
- Vibration
- Yaw of the airplane caused by thrust imbalance
- High Exhaust Gas Temperature (EGT)
- Change in the spool speeds
- Smoke/odor in cabin bleed air
- Engine Pressure Ratio (EPR) change
- Flock of birds in the immediate vicinity

Several of these should occur TOGETHER, would a pilot diagnose a FOD event if only one symptom is evident?

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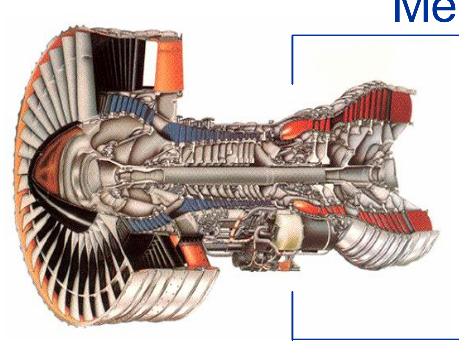
Why Develop This System?

- System developed to raise the level of autonomy of the engine and thus reduce pilot workload
- Most FOD events occur close to the ground where pilot workload is greatest
- Pilot procedures in place to evaluate engines with suspected FOD once safe altitude is reached, easier for pilots if potentially damaged engines are identified
- Rejected take-off due to suspected FOD is a cause of accidents
- Even if no obvious damage, impact can produce cracks that can be propagated through high-cycle fatigue

Problem Setup

Engine Simulation Structural and Aerothermal

Accelerometer Measurements



Gas Path Measurements

FOD DETECTION DATA FUSION SYSTEM

Expert Consensus (or not)

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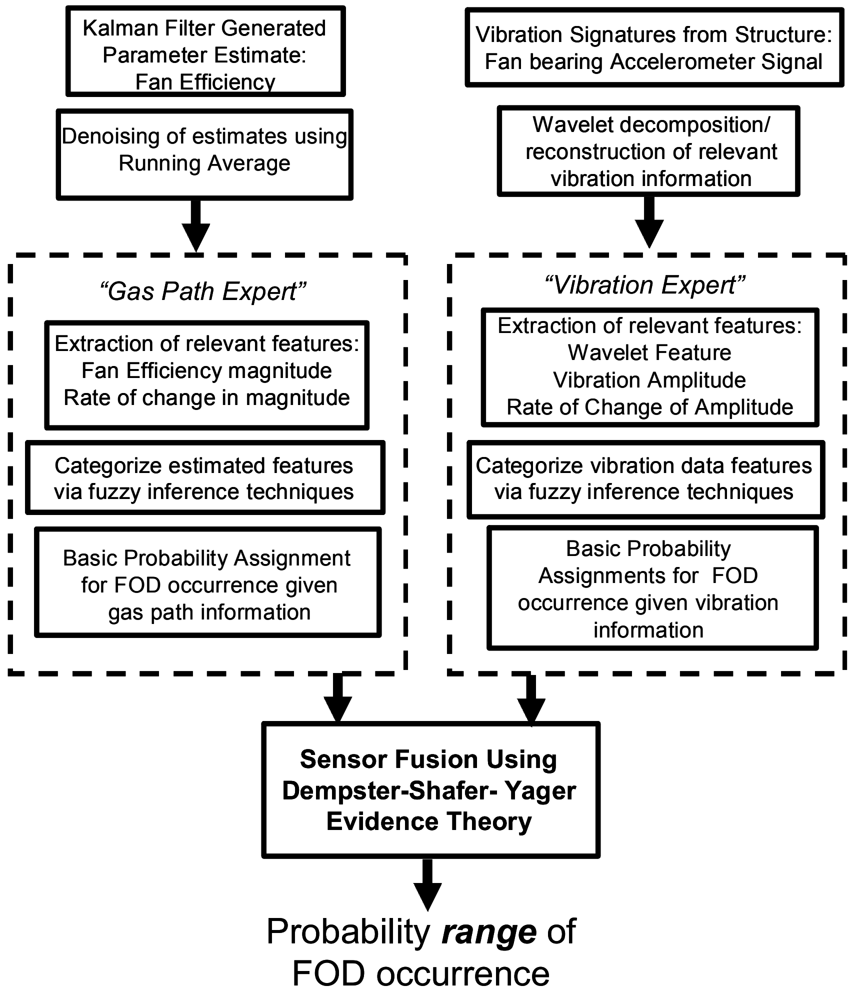
Use Tools to Analyze Data and Extract Features and Fuse

- A Kalman Filter can analyze gas path data to estimate shift in fan efficiency
- Wavelet analysis can be used to identify the signature of an impulse due to impact from accelerometer data.
- Fuzzy logic can be used to interpret features extracted from the data
- Dempster-Shafer-Yager Theory to combine expert opinions while accounting for conflict

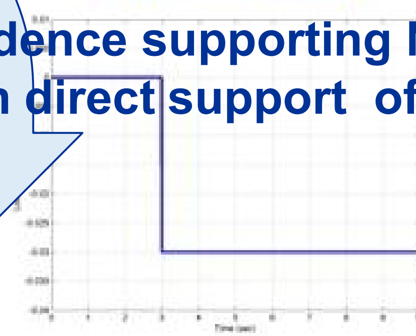
FOD Detection Data Fusion System Overview



Foreign Object Ingestion Detection Data Fusion System

EFFICIENCY SHIFT MANIFESTS ITSELF AS SHIFTS IN MEASURED VARIABLES

Fan Efficiency



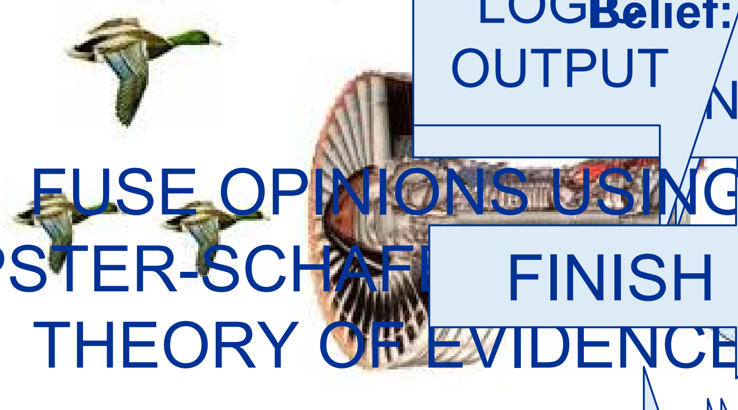
Aerothermodynar
- components: effic
- engine: RPM, thru

FUZZY LOGIC OUTPUT

Plausibility: 1 – (all evidence supporting NOFOD)

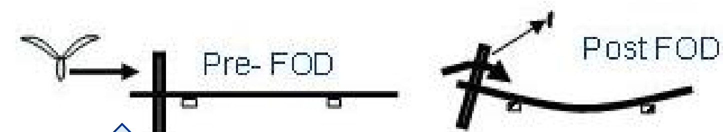
Belief: all evidence in direct support of FOD

NG



FUSE OPINIONS USING DEMPSTER-SCHAFER THEORY OF EVIDENCE

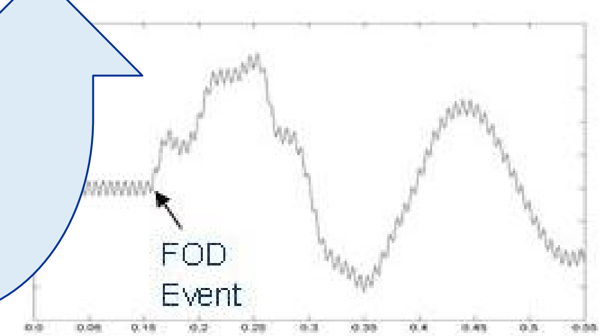
FINISH



Structural Resp
- rotor bearing v

FUZZY LOGIC OUTPUT

NG



Final Comments

- This work was performed using simulated data and best guesses based on the very limited literature on FOD events. The system provides a framework for more expert knowledge
- The framework is flexible and modular
  - The structure facilitates the incorporation of additional experts in parallel
  - The existing fuzzy rule bases can be changed easily based on the acquisition of expert knowledge
  - Additional features can be easily added to the rule bases